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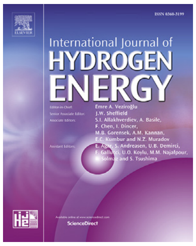

Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes

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ABSTRACT

The paper presents techno-economic analyses and life cycle assessments (LCA) of the two major gasification processes for producing hydrogen from biomass: fluidized bed (FB) gasification, and entrained flow (EF) gasification. Results indicate that the thermal efficiency of the EF-based option (56%, LHV) is 11% higher than that of the FB-based option (45%), and the minimum hydrogen selling price of the FB-based option is $0.3 per kg H_2 lower than that of the EF-based option. When a carbon capture and liquefaction system is incorporated, the efficiencies of the EF- and FB-based processes decrease to 50% and 41%, respectively. The techno-economic analysis shows that at a biomass price of $100 per tonne, either a minimum price of $115/tonne CO_{2e} or a minimum natural gas price of $5/GJ is required to make the minimum hydrogen selling price of biomass-based plants equivalent to that of commercial natural gas-based steam methane reforming plants. Furthermore, the LCA shows that, biomass as a carbon-neutral feedstock, negative life cycle GHG emissions are achievable in all biomass-based options.

Introduction

Hydrogen is a useful chemical with extensive applications in crude oil refining and upgrading, the production of methanol, ammonia and other chemicals. Hydrogen also continues to attract attention as a carbon-free fuel option for the transportation sector. Although commercial H_2 production plants are relatively CO_2 intensive (with emissions of approximately 9–11 kg CO_2 per kg H_2 in a typical natural gas-based H_2 plant [1,2]), most of the current bulk scale hydrogen production plants use fossil fuels without a carbon capture and sequestration (CCS) system [3]. Therefore, reducing CO_2 emissions associated with the production of hydrogen could result in considerable reductions in emissions from refineries and other sectors that consume hydrogen. Producing hydrogen from renewable resources (e.g., biomass [4,5], wind or solar energy [6]) or fossil fuel systems with CCS [7] is an active research area, with potentially significant environmental implications.

Biomass is a renewable energy resource that can be used instead of fossil fuels for hydrogen production. Unlike

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conventional processes for hydrogen production from natural gas, the hydrogen from biomass is a clean energy carrier [8,9]. There are two main routes for the conversion of biomass to hydrogen: thermochemical and biological pathways. Several works have been performed in the development and analysis of biological hydrogen production from biomass [10–14]. However, overall, thermochemical processes are found to achieve higher energy efficiency and hydrogen yield [15]. Among different conversion methods, biomass gasification is a financially viable hydrogen production option [5], where carbon is converted to syngas (H_2+CO) through an endothermic reaction and in the presence of steam. Tao et al. [16] performed techno-economic analysis and life cycle assessment (LCA) of biomass thermochemical utilization for isobutanol, n-butanol, and ethanol production processes. According to their results, producing ethanol was the more financially attractive pathway for the biomass conversion. In parallel, Spath et al. [17] compared the production cost ($/GJ) of different transportation fuels from biomass and reported that hydrogen was the most profitable route. Turn et al. [18] also studied hydrogen production from biomass using a bench-scale fluidized bed gasifier. Their results showed that the highest hydrogen yield was achieved at the gasification reactor temperature of 850 °C.

Koroneos et al. [19] performed a LCA of various hydrogen production technologies, and showed that, compared to a natural gas reforming process, using biomass as a feedstock can reduce the greenhouse gas (GHG) emissions by approximately 75%. Moreover, Susmozas et al. [20] studied the life cycle environmental performance of a poplar indirect gasification pathway and compared the results with typical natural gas reforming technology. They found that the biomass gasification pathway can be a promising alternative to natural gas reforming technology, with significant reductions in GHG emissions (0.4 versus 10.6 kg CO_{2e} per kg H_2) and fossil fuel demand.

Despite considerable reported environmental benefits of biomass utilization for hydrogen production, there remain some barriers in the commercialization of these systems [21]. For instance, the conversion efficiency of biomass-based systems is 20–70% lower than those of the conventional natural gas steam reforming processes [22]. Furthermore, due to the relatively low H_2/CO ratio of the biomass gasification synthesis gas [23], higher energy consumption for the energy intensive syngas upgrading units (water gas shift reactors), and purification units (CO_2 removal using amines and PSA) are expected. The syngas composition depends on the steam to biomass ratio, gasification temperature, and more importantly, the gasifier technology. The biomass gasification technology affects the capital cost and energy efficiency of the plant. Various gasification configurations have been developed in recent decades, each with advantages and limitations. Most of the commercial gasifiers are either oxygen (or air)-blown, or operate based on an indirect heating system. Among these technologies, fluidized bed (FB), fixed bed, and entrained flow (EF) gasifiers have been extensively studied and experimentally tested for commercialization [24]. Ersoz et al. [25] performed a simple steady-state process simulation for hydrogen production from biomass in Aspen Hysys. However, previous studies lack comparative techno-economic analysis and LCA of environmental impacts of technologies for a commercial scale biomass-based hydrogen plant.

Several gasification systems have been developed for syngas production from solid feedstocks. Fixed/moving-bed downdraft or updraft configurations have a simple construction compared to other types of gasification systems. However, these types of gasifiers require a high residence time [26], have relatively poor carbon conversion [27], may have considerable tar formation, depending upon the selection of updraft or downdraft options [28], and tend to be suitable for small scale power plants [26,29]. A FB gasification reactor is another option in which a uniform temperature distribution can be achieved in a shorter residence time [26]. Fluidized bed gasifiers are also flexible with respect to feedstock type and composition, which makes them a suitable option for scale-up [26,28,30].

Indirect circulating FB gasification is a novel option that has been developed to avoid product syngas combustion inside the gasification reactor and also to avoid syngas nitrogen dilution, without use of high purity oxygen [29]. In this design, the heat for gasification is provided indirectly using a circulating heat transfer solid (e.g., olivine and dolomite) [31]. Olivine sand is heated in a separate but interconnected combustion reactor, through combustion of either natural gas, or the char formed in the gasifier. Due to indirect heat transfer and also to avoid uneven fluidization [32], FB gasifiers operate at relatively low temperatures. As a result, the biomass conversion to syngas is relatively low and these systems require a downstream reforming unit to convert tar and other hydrocarbons to H_2 and CO [33]. Spath et al. [34] carried out a detailed techno-economic analysis of hydrogen production via biomass FB gasification technology. Their results showed that the overall thermal efficiency of the plant was 45.6% (LHV), with a minimum hydrogen selling price of $1.38/kg H_2 when the biomass feedstock cost was $30/tonne.

Extensive work has been aimed at overcoming the above noted challenges and improving gasification performance and biomass conversion. Forschungszentrum Karlsruhe and Future Energy developed a biomass gasification pilot plant using EF gasification technology [35]. Entrained flow gasification is a commercially available technology that has been used for decades by Shell, ConocoPhillips and General Electric Energy for coal and petcoke gasification [32,36]. When EF technology uses a biomass feedstock, the biomass is partially combusted inside the gasifier, which results in higher gasification temperatures than the indirect FB gasification approach [18,32]. Due to the higher gasification temperatures, tar cracking occurs inside the gasifier and the produced syngas is free of tar. Larson et al. [37] assessed the attractiveness of producing various fuels from switchgrass using EF gasification, and showed that by producing hydrogen, the highest thermal efficiency (63.5% LHV) was achieved.

Another advantage of EF gasifiers is their relatively high carbon conversion in a short residence time (a few seconds in most EF gasifiers, compared to a few minutes in other types of gasifiers [32]), which significantly reduces the size and cost of the gasifier. However, since direct gasification with air dilutes the produced syngas, air-blown gasifiers are not recommended for commercial-scale biomass gasification [38]. Air-blown gasifiers produce low-quality syngas, which is

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